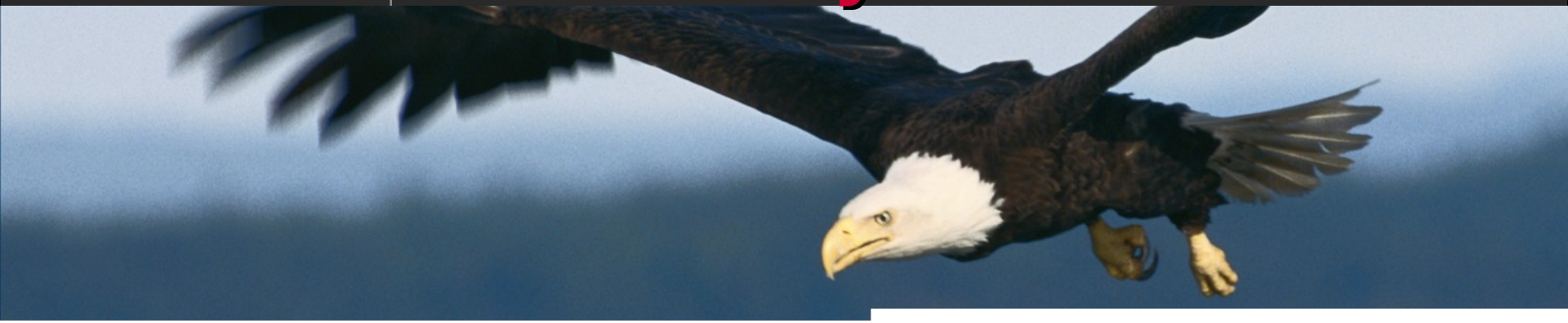
Systems Engineering of Complex Adaptive Systems



Otto Jons

National Defense Industrial Association

6th Annual Systems Engineering Conference (Oct. 2003 San Diego)

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EXPERIENCE. RESULTS.

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Preface

EXPERIENCE. RESULTS.

- **A rigorous scientific basis for Complex Adaptive Systems: - Still in its infancy**
- **Popular science flavor of books by Gleick (“Chaos”) and Waldrop (“Complexity”): - Disdain (?) by some “serious” scientists and engineers**
- **Some advances by scientists: See Holland (“Hidden Order” and “Emergence”)**

However:

- **Complex Adaptive System: - Profoundly important**
- **Some “lessons (-ready to be-) learned”**

Outline

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- Systems Engineering: – A Very Brief Review
- The Systems Spectrum
- Complex Adaptive Systems
- Developing (Elements of) CAS
- Summary and Conclusions

The Systems Engineering Process

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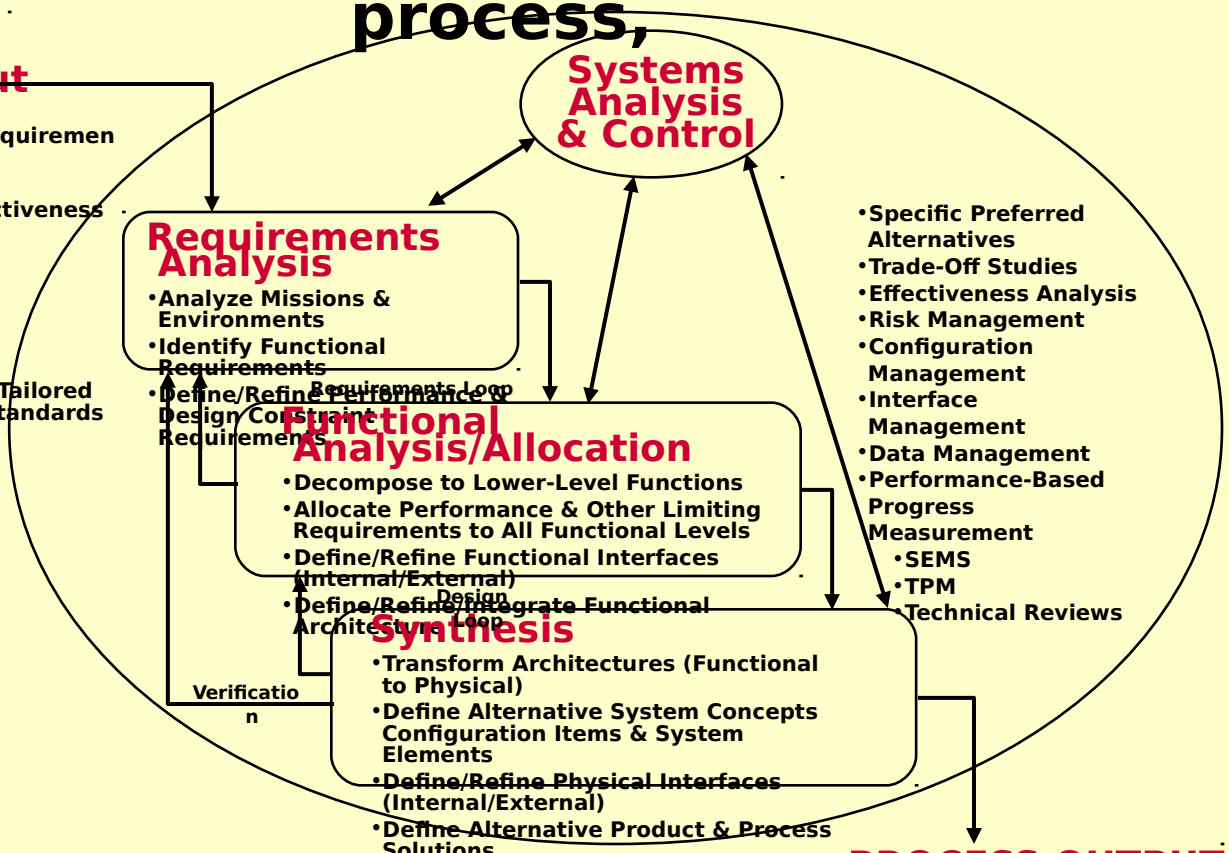
Current doctrine has matured into a standard process,



-a process applied to any system.

Naval System Hierarchies (Examples

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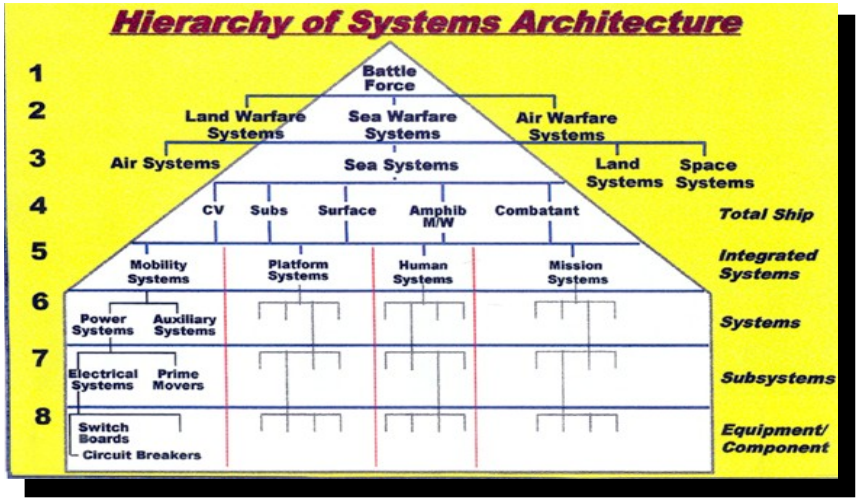
System Hierarchies:

The Vertical Dimension



- Nation
- Government
- DoD/Navy
- Joint Force
- Battle/Task Group
- Ship
- Machinery System
- Propulsion System
- Engine
- Fuel Pump

How about the Horizontal Dimension ??

Are there different System

Outline

EXPERIENCE. RESULTS.

- **Systems Engineering – A Brief Review**
- **The Systems Spectrum:**
  - **Spectrum Samples**
  - **The Limits of Engineering**

The Systems Spectrum

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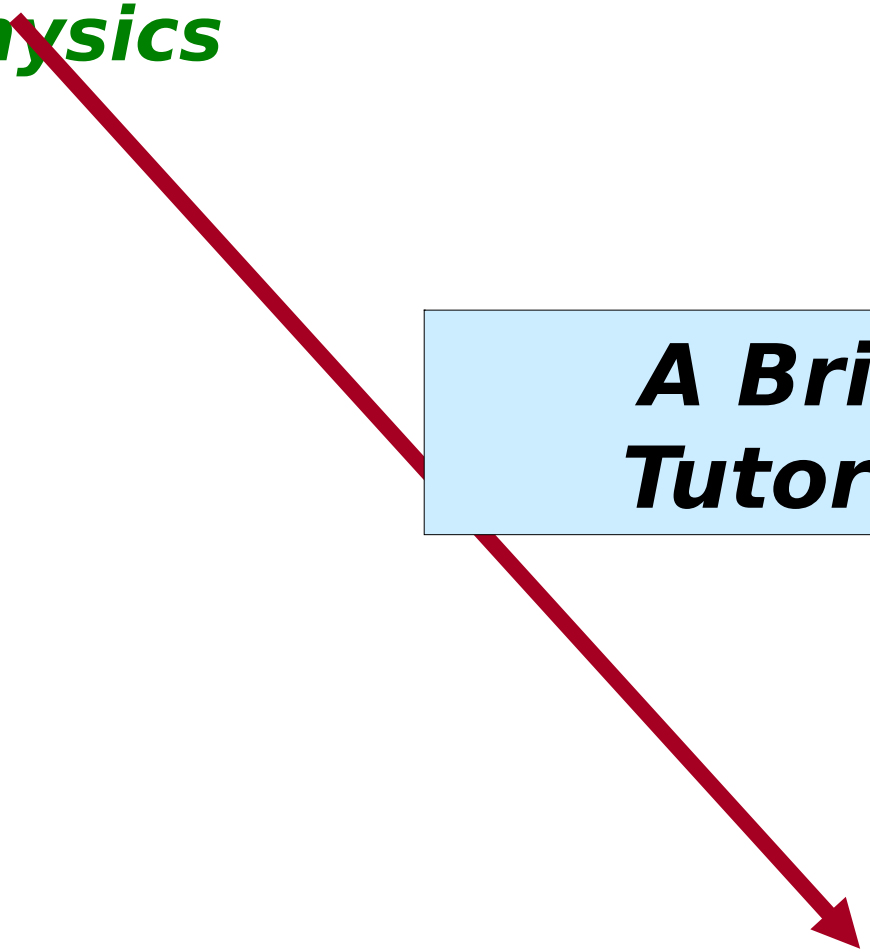
From Newtonian Physics



A Brief Tutorial

To "New Science"

The Systems Spectrum

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- **Traditional Engineering Systems (TES)**

=Newtonian/Mechanistic:

=”Action equals Reaction”, etc.

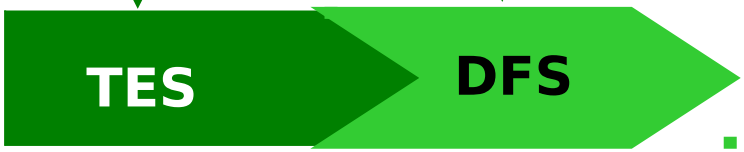
=The Foundation of Technology

TES

- ***Current SE Doctrine focuses (-exclusively??) on TES:***
  - ***Development of an Optimal System for a Specified Need / Operation***

The Systems Spectrum

- **Traditional Engineering Systems**
- **Dynamic Feedback Systems**



e.g., Double Pendulum; - seemingly simple, but…..

The Systems Spectrum

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- **Traditional Engineering Systems**

Dynamic Feedback Systems

Complex "Chaotic" Systems

e.g., Weather System; highly complex, also involving dynamic feed-back

The Systems Spectrum

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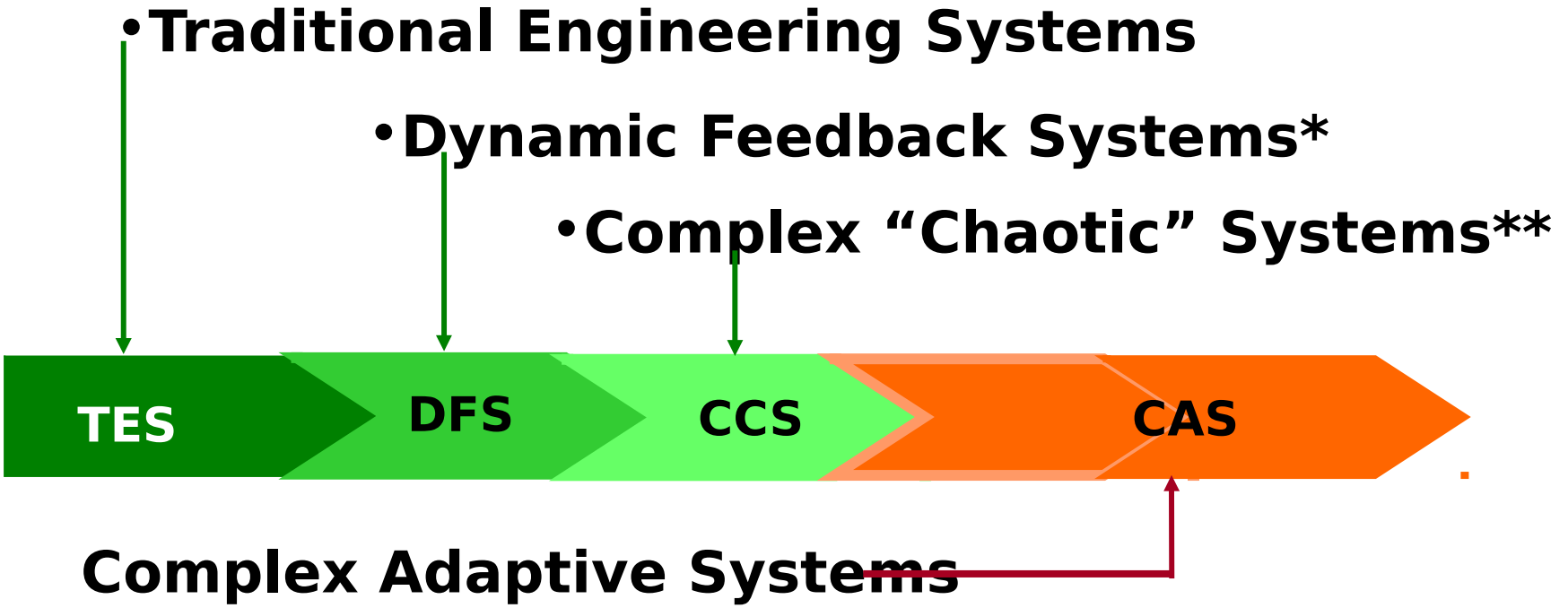
- **Traditional Engineering Systems**
- **Dynamic Feedback Systems***
- **Complex "Chaotic" Systems****

- DFS & CCS obey the laws of physics, however: Prediction of long-term behavior not possible because of extreme sensitivity to initial conditions

The Systems Spectrum



= Characterized by “Adaptive Agents”

The Systems Spectrum

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- **Traditional Engineering Systems**
- **Dynamic Feedback Systems***
- **Complex "Chaotic" Systems****

Complex Adaptive Systems:

Reactive CAS

= Ecology; Natural systems, such as the Immune System;

The Systems Spectrum

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- **Traditional Engineering Systems**
- **Dynamic Feedback Systems***
- **Complex "Chaotic" Systems****

Complex Adaptive Systems:

Reactive CAS

Proactive CAS

=Economies, Games, Conflicts, Warfare:
Conscious decision-making by

The Systems Spectrum

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- **Engineering (-and Systems Engineering), to date: Focus almost exclusively on TES**
- **Traditional engineering encounters increasing limitations**

- **Warfare Systems are generally P-CAS**
- **They may be R-CAS if threat-based**
- **They may have TES - or R-CAS subsystems**

Systems Spectrum - Implication

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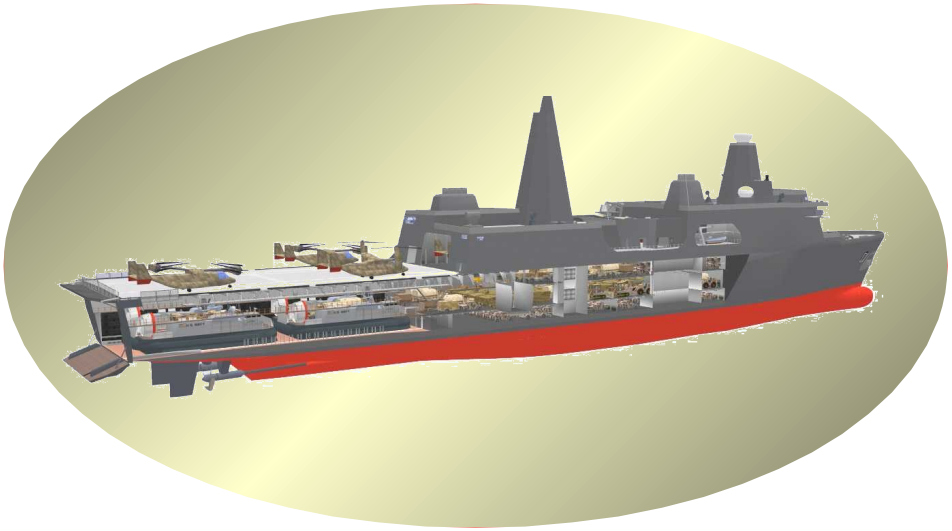
Traditional Engineering Systems

Proactive CAS

Explore differences between TES & P-CAS:

Use the *Naval Ship System:*



- **Sheer Size & High Cost:**

  ~ i.e., No Prototyping

- **Long Life Span:**

  ~ 40+ Years

Systems Spectrum - Implication

The Naval Ship System: A Hybrid System

The Hull: A Transportation System

The Weapon Suit: A Warfare System

(Often with a Transportation Subsystem)

- *40+ Years Lifespan*
- *(Generally:)*

Mature Technology

- *2 to 10 Years Lifespan*
- *(Generally:)*

Advanced Technology

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The Naval Ship System: A Hybrid System

In Part = A Transportation System

In Part = (Part of) a Warfare System

(Often with a Transportation Subsystem)

These Differences :

- **Manifest themselves in the ways Effectiveness is established**
- **Warrant differing development approaches**

Effectiveness of a TES

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(A Shuttle Ship: A pure Transportation System:)

$$\text{Effectiveness (E)} = \frac{\text{Payload (P) X Distance (D)}}{\text{Time (T)}}$$

$E = P \times D / (Tp + Ts)$

$= P \times D / (Tp + D / V)$

Where: Tp – Time in Port

Ts – Time @ Sea

V - Speed

Note: - A Mathematical Relationship can be established between System Performance and Effectiveness.

- The Objective is achieved largely by the System's *Output*.

Outline

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- Systems Engineering – A Brief Review
- The Systems Spectrum:
- Complex Adaptive Systems (CAS):
  - Effectiveness of P-CAS
  - Adaptation / Implication for Warfare Systems

Effectiveness of P-CAS

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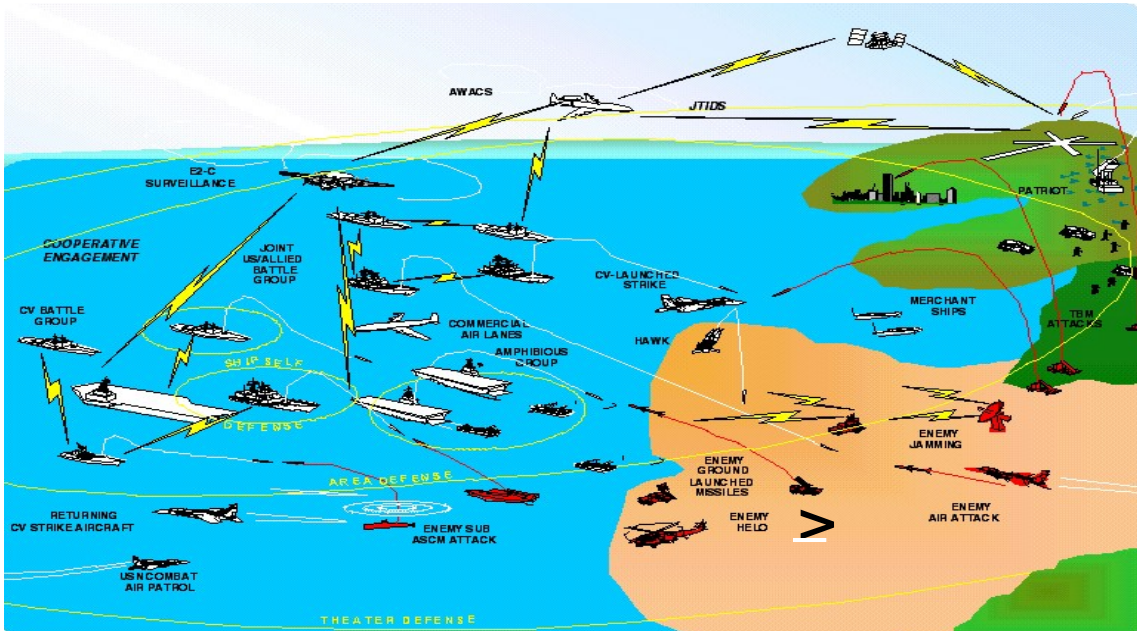
Mission Success / Effectiveness: *Outcome* (Not: Output)

Planned Outcome →



→ **Actual Outcome**

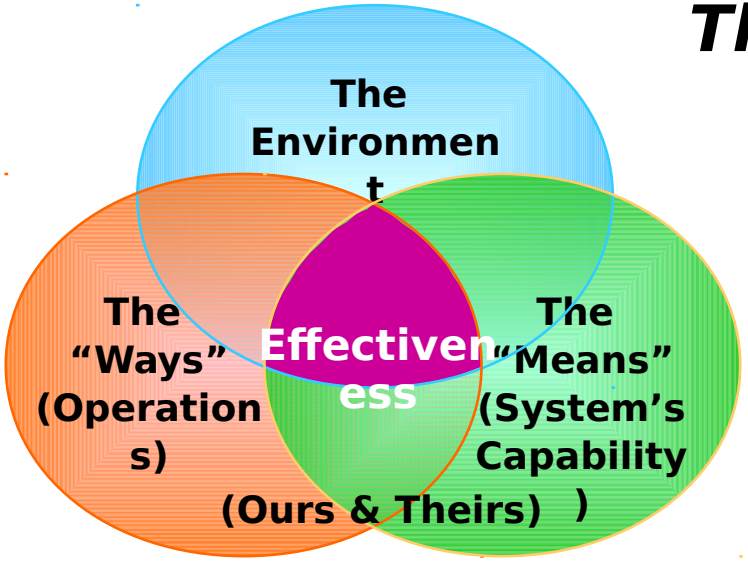
Mission Success : Planned Outcome ≤ Actual Outcome

Parameters:

- **Systems Deployed (The "Means") & Their Capability**
- **Strategies, Tactics, CONOPS (The "Ways")**
- **The Environment/ its Effect on "Means" and "Ways"**

("Ways" & "Means": Both "Ours -" & Theirs -")

Effectiveness of PCAS (Cont.)



The Goal:

Accomplishing an Objective:

= Winning a Battle

= Succeeding in …

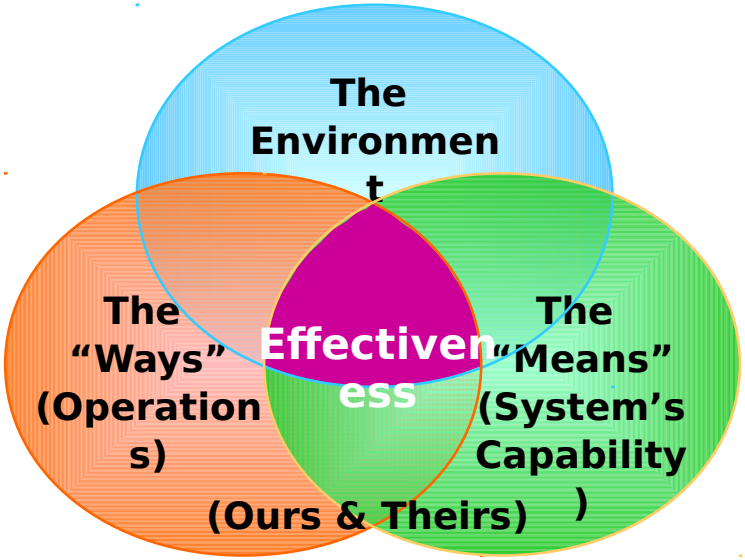
..(Name it)

= Winning a Game of …..

…Chess where:

- **The "Environment" (Board) is fixed**
- **The "Means": The Performance Capabilities of the pieces are defined and fixed**
- **Effectiveness (= Winning) is then solely a function of the players' "Ways": How they play, react to and anticipate the opponent's moves**

Effectiveness of PCAS (Cont.)



(Another Example:)

The Mission:

Winning a Football Game

- **The "Environment"/Field is Fixed and Further Neutralized by Switching Sides at Halftime**
- **The "Means": The Performance Capabilities of the Teams, as Units (Offensive -, Defensive – and Special Teams) , Individuals, Their Natural Ability, Conditioning, Training,**
- **The "Ways" involve the Play-Book, the Plays Called and the Reaction of the Defense**
- **Effectiveness (= Winning) is a Function of "Ways" and**

Observations re. Warfare

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- **Proactive Adaptation in Warfare:**
  - All about the Creation of Asymmetries (= greater strength at the point of contact)
- **Asymmetries may be created**
  - "Locally"; - in the same general physical environment (maneuver warfare)
  - In an entirely different environment
- **Adaptation: More likely to be effective if it is <u>not</u> anticipated by the adversary**
- **Warfare: Need not be proactive-adaptive; May be re-active-adaptive**
- **Sun Tzu's teachings:**
  All about Proactive Adaptation,

Proactive Adaptation in Warfare

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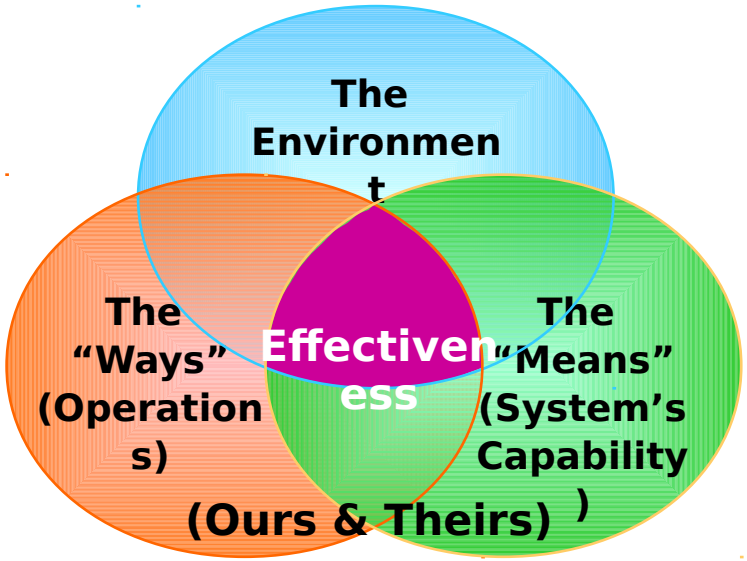
Scope of Adaptation :

- "Ways" - Speed (How Fast)
  - Quality (How Well)
- "Means" – Use of Existing Resources
  - Future System Development



Warfare Examples Using Existing "Means":

- Environment (Choice)
  - Boyd's OODA Loop: "Ways" (Speed & Quality)
  - Salamis, Trafalgar: "Ways" & Environment

Warfare Examples Using New "Ways" & "Means":

- Phalanx / Alexander the Great:

  Minor modification of "Means" & "Ways":

  Vastly improved Effectiveness

Effectiveness , Performance & Cost

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- **Success** in warfare:
  - A function of **effectiveness**
  - A Measure of the **outcome** of the battle
- **Effectiveness** results from
  - The **combination of "Ways" & "Means", ours & theirs,** in the **environment** of contact
  - = **Not** (necessarily) from the **performance** / **capability of our systems** ("Means")
- **However: Cost = f (Performance)**

Cost = f (Effectiveness)

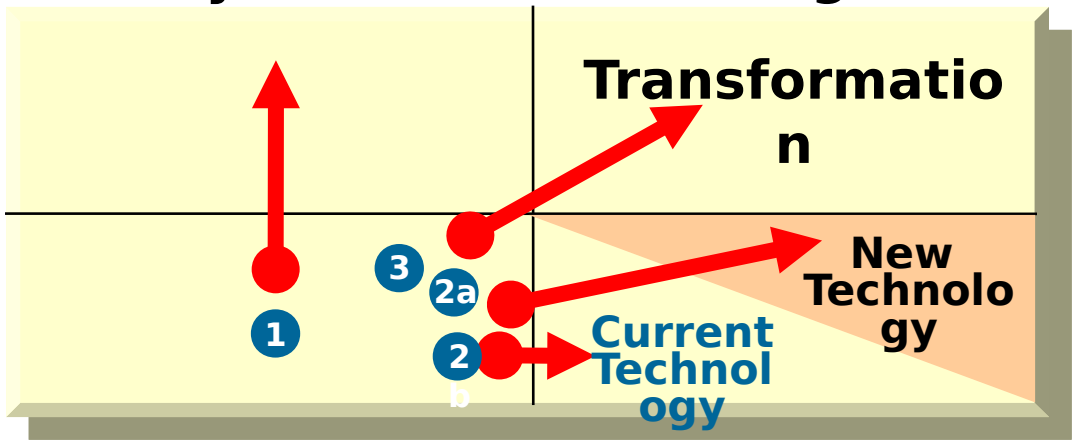
Effectiveness is established:

- In the "Ways" & "Means" Trade-Space;
- Not: in the Performance & Cost Trade-

The “Ways” & “Means” Trade-Spa

Improving Mission Effectiveness

1. Find Better ‘Ways” of Using Existing “Means”
2. Retain Current “Ways” but Develop Improved “Means”
    a. With Current Technology
    b. With New / Advanced Technology
3. Develop New “Ways” to Take Advantage of New “Means”



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- Developing (Elements of) CAS
  - Systems “Engineering”(?) of CAS

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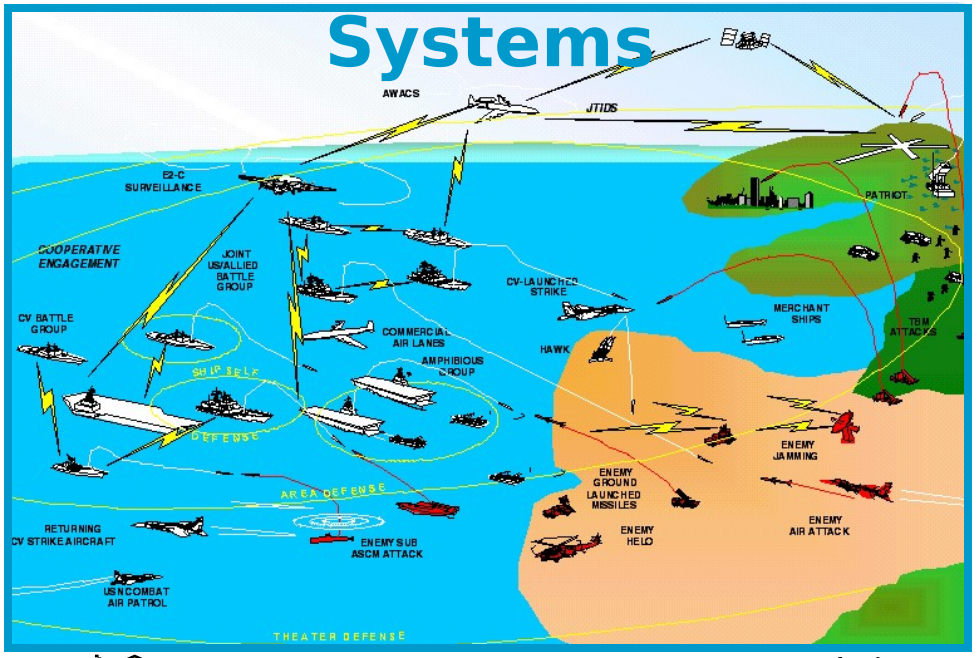
The Warfare System of Systems



Material Support

Operations Development

Personnel Support/ Dev't

ILS

Personnel

Requirements (MNS, ~~ORD~~)

(ICD, CDD)

Material Development

Personnel Development

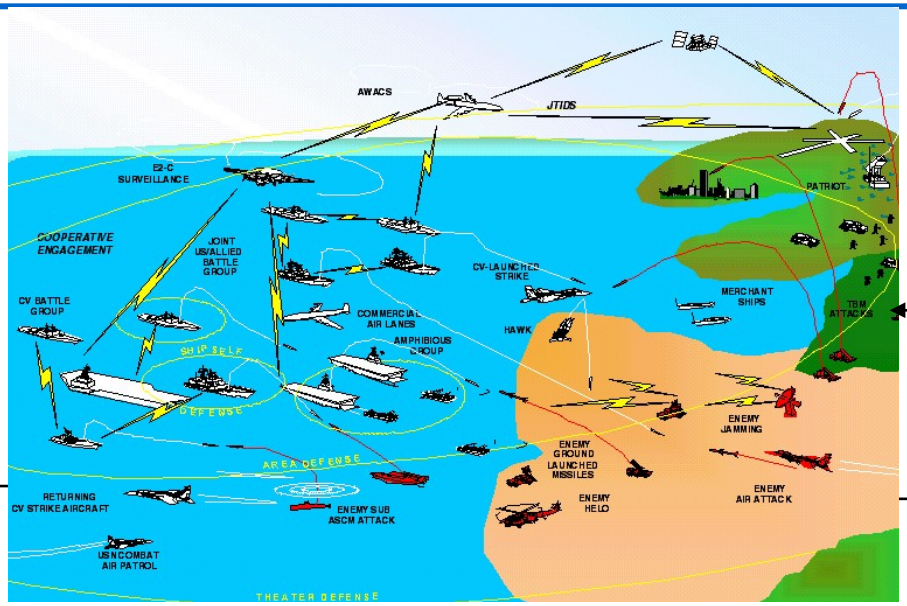
Manning

The Acquisition System

Ship System Developm

EXPERIENCE. RESULTS.

System of Systems



Mission Analysis

Planned Use

How Used

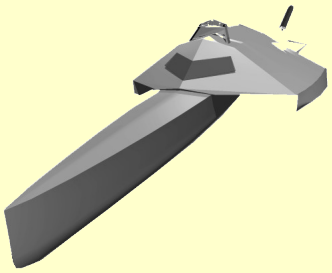
Value

Mission Effectiveness (MOE)

Functional Allocation

Performance Capabilities/ Requirements

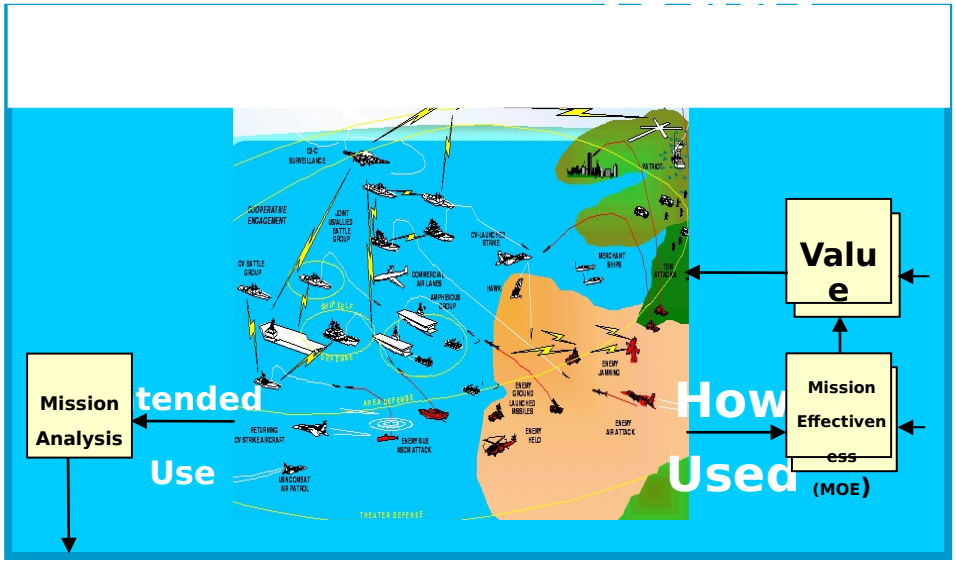
Developing/Acquiring Systems



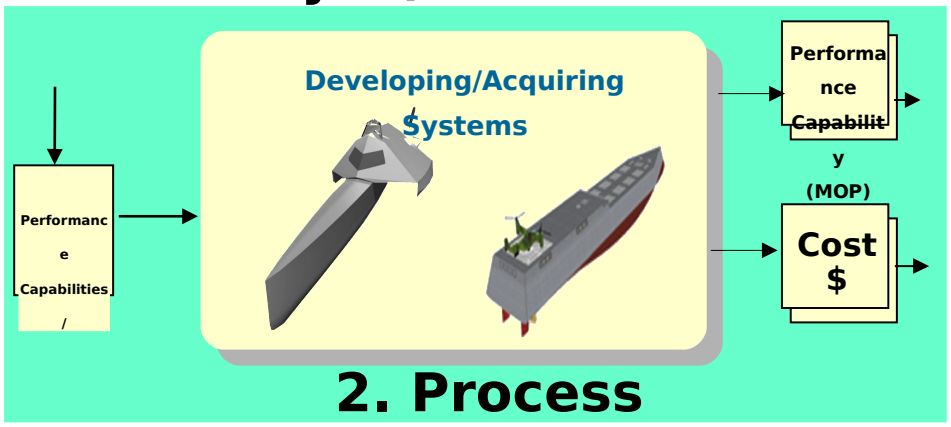
Performance Capability (MOP)

Cost $

Ship System Development - Today



1. Input "Ways")



2. Process

- **The Process is generally executed sequentially since:**
- **Rarely are CONOPS modified as the result of design results**
- **Requirements are "engineered" to respond to operational needs and perceived needs for**

Requirements are to be met;

- not to be negotiated !!

3. Output ("Means")

Systems Engineering Process for TES

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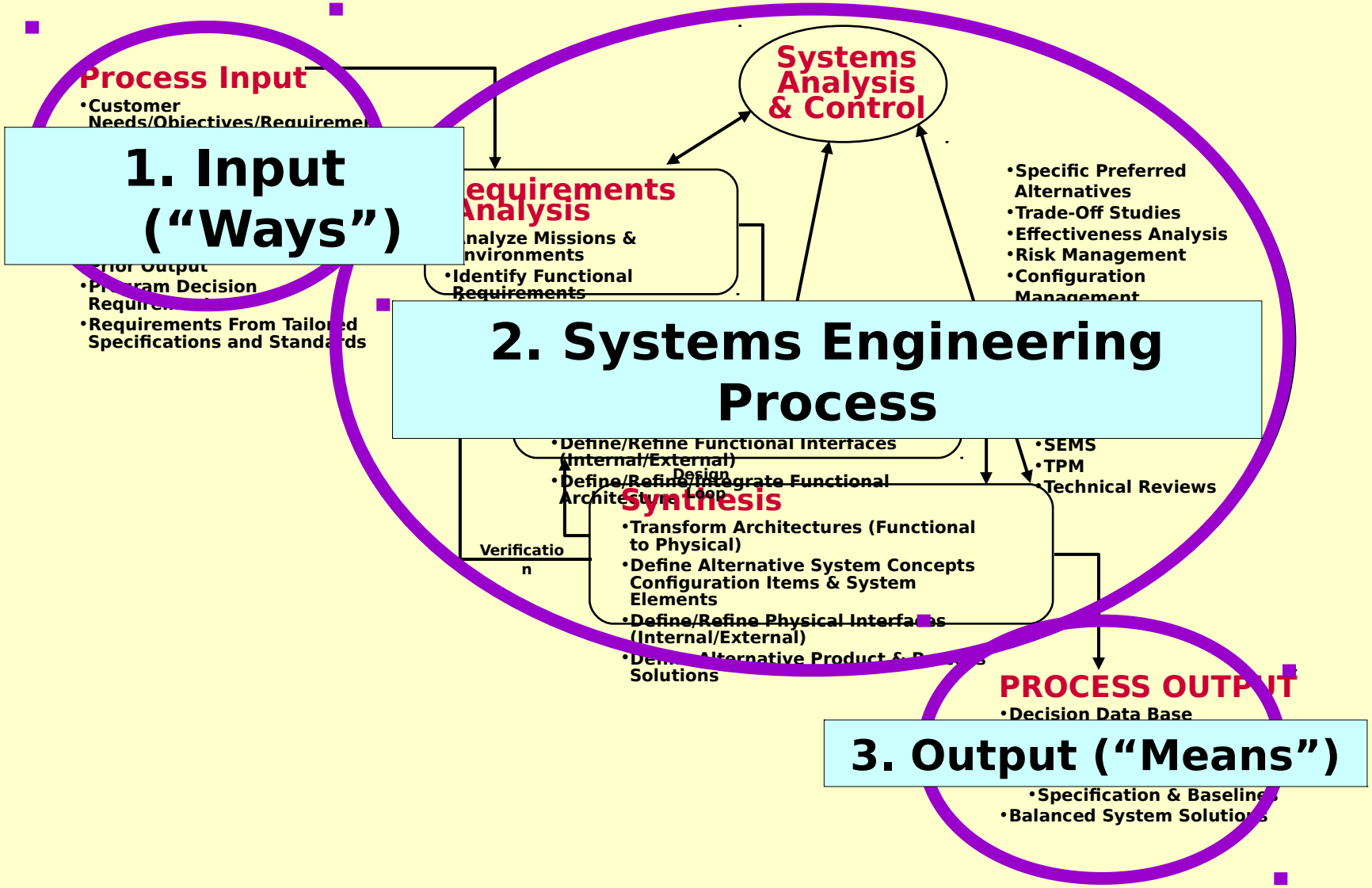

SE Process for P-CAS

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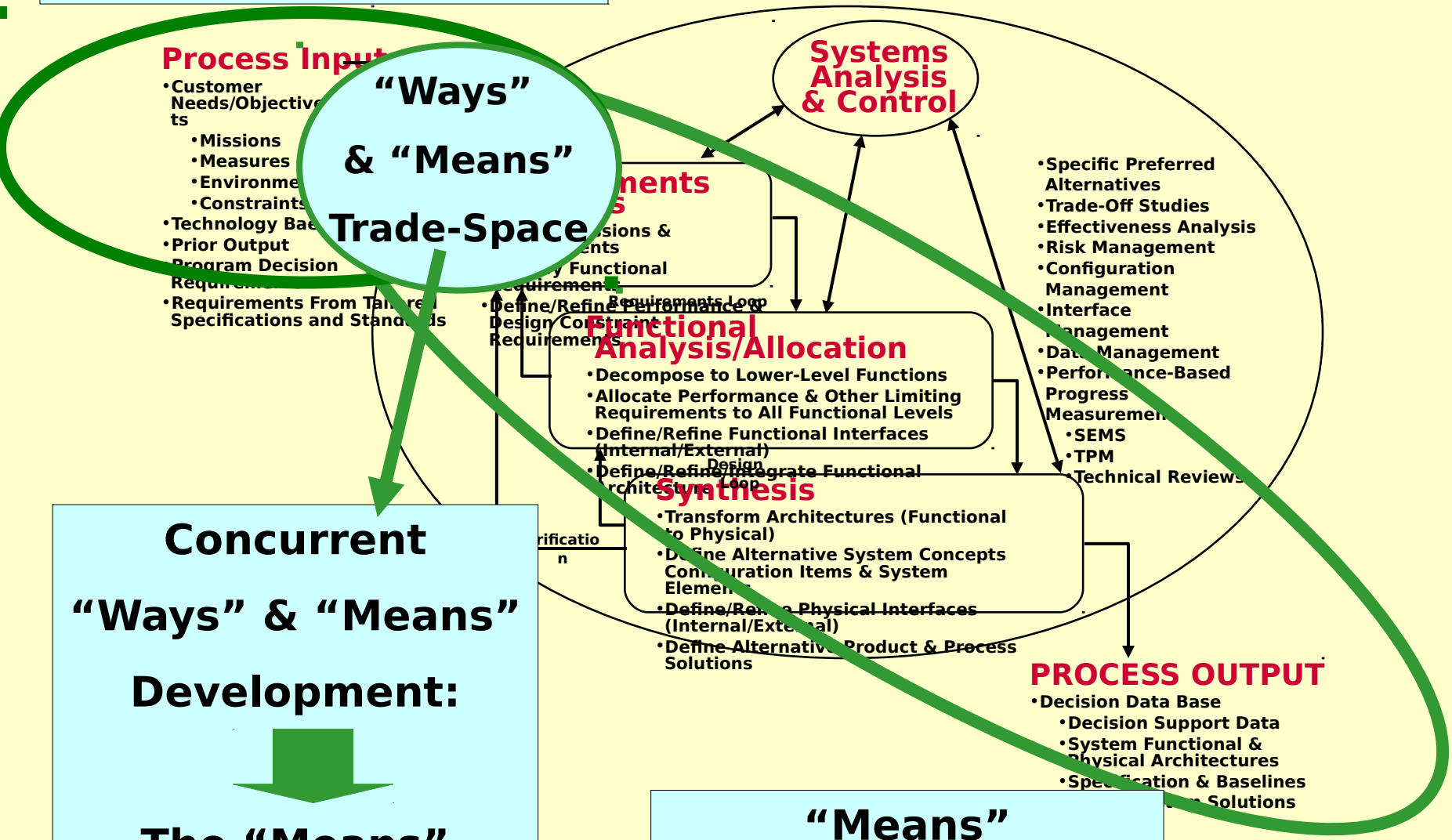
"Ways" Development



Concurrent "Ways" & "Means" Development:

The "Means" Solution

"Means" Development

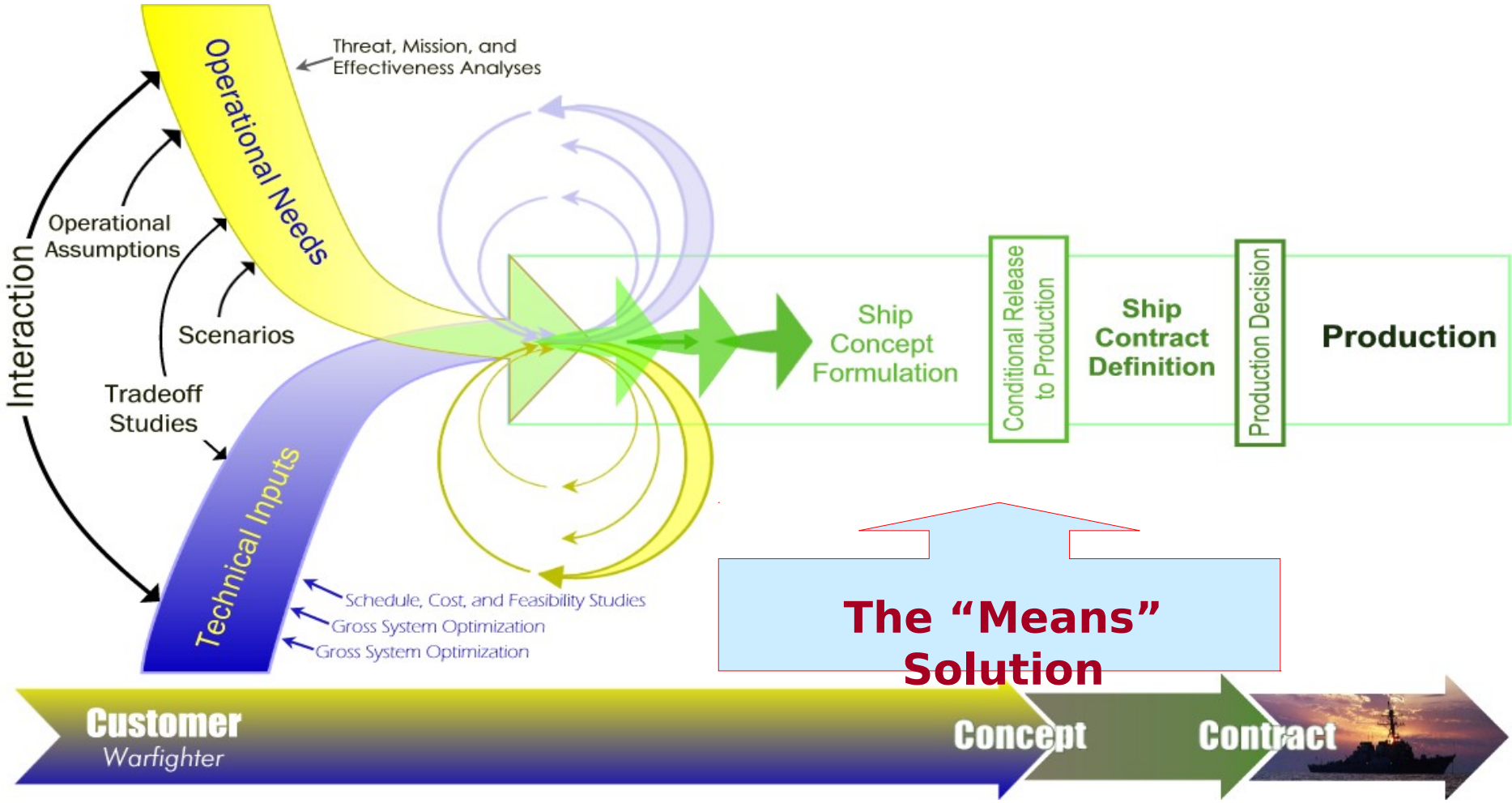
For P-CAS, in particular… :

- **Both performance capability and cost are design-dependent , require some system definition because**
  - **It is not possible to assess a system's performance capability or even technical feasibility without a design definition**
  - **It is rarely possible to develop reliable cost estimates for new systems solely on the basis of performance requirements.**
- **Cost information is crucial to make prudent decisions regarding quality versus quantity**

- **Valid performance predictions and cost estimates must be based on a Design Definition**
- **The "Ways" & "Means" Trade-Off is incomplete if only the Required Capability is identified**

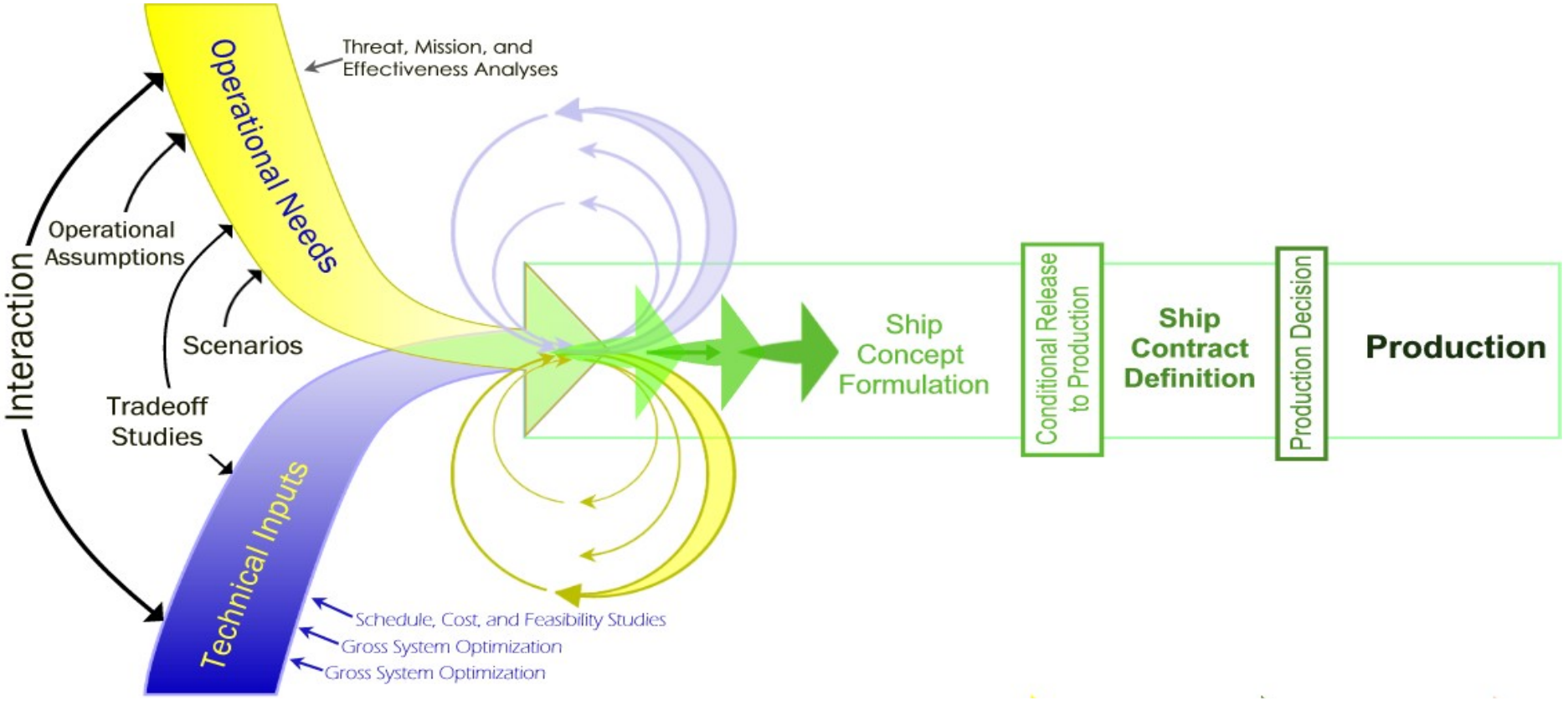
A"Means" Solution must be defined !

The "Ways" & "Means" Trade-Off



Solution – Based Acquisition

The "Ways" & "Means" Trade-Off



Credits:

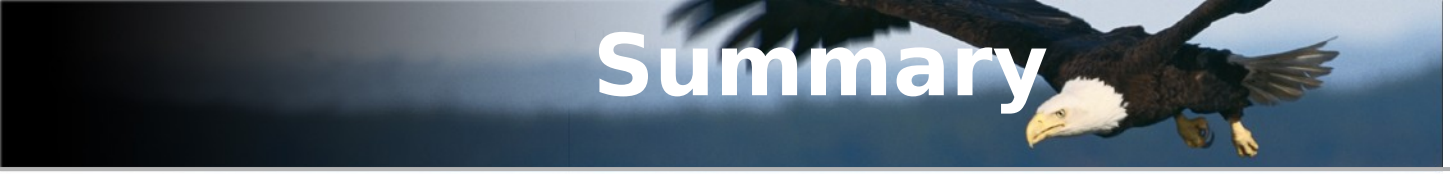
NAVSHIPS 0900-060-0100, "Guide for Conducting Ship Concept Formulation", Figure 2-4, page 2-16, 1969 A.D.

Summary

- Systems form a Spectrum ranging
  - from Traditional Engineering Systems (TES)
    - to Complex Adaptive Systems (CAS)
- CAS may be Reactive (R-CAS) or Proactive (P-CAS)
- P-CAS are of special interest to the Defense Industry
- TES display a strong link of System/"Means" Performance and Effectiveness
- In Proactive CAS, this link is often very weak:
- It is greatly diluted by
  - how and where we use systems ("Our Ways") and
  - the adversary's "Ways" and "Means"

This challenges the Sanctity of Performance Requirements

Summary



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(For Proactive Complex Adaptive Systems, such as Warfare Systems, in particular…)

- **Requirements must "float" until the Exploration of the "Ways" & "Means" Trade-Space has been completed**

  Only the user can determine which combination of "Ways & Means" will be most effective

- **Completion entails the selection of the "Means" Solution based on effectiveness, capability and cost**

- **This requires a good definition;**

Therefore:

"Definition before Acquisition";

therefore: Solution-Based Acquisition